TRANSIENT GAMMA-RAY SPECTROMETER OBSERVATIONS OF GAMMA-RAY LINES FROM NOVAE. III. THE 478 keV LINE FROM ^{7}Be DECAY

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ABSTRACT

The *Wind* spacecraft carrying the Transient Gamma Ray Spectrometer (TGRS) moves in an extremely elliptical orbit that largely avoids Earth's trapped radiation belts and albedo γ-radiation. The TGRS therefore enjoys a relatively low level of background that is also extremely stable. We show how this stability enables modeling of the time variability of background lines, which in turn enables a novel technique of background subtraction to be used in the detection of transient astrophysical lines. We apply a simple version of this method to the line at 478 keV that is expected to arise from nucleosynthesis of ^{7}Be in nearby novae. This search covers the entire southern ecliptic hemisphere during 1995–1997, including five known individual events, and possible undiscovered individual events. The TGRS design also uses *Wind*'s 3 s rotation period to modulate signals from the Galactic center (GC). We use this feature of the instrument to search for a quasi-constant level of 478 keV emission from the accumulation of ^{7}Be from several novae that are expected to occur in the direction of the GC during that isotope's 53 d half-life. We derive upper limits on the transient (single-nova) emission which improve on previous limits by about an order of magnitude, and limits on the steady (many-nova) emission which represent a factor 2 improvement. Only weak limits can be placed on the key parameters in the nucleosynthesis and ejection of ^{7}Be, however.

Subject headings: gamma rays: observations — novae, cataclysmic variables — white dwarfs

1. Introduction

Although clasical novae occur rather frequently in our Galaxy (some tens of events per year), they are not expected to contribute greatly to the chemical enrichment of the Galaxy because they eject relatively small masses of nuclear-processed material. The rare CNO nuclei ^{13}C, ^{15}N and ^{17}O are exceptions, and so is the light isotope ^{7}Li, which is the topic of the present study (Hernanz & José 2000). About 10% of the present Galactic abundance of ^{7}Li may have come from novae, which are one of the several sources (mainly cosmic ray spallation and neutrino spallation in supernovae: Cassé, Vangioni-Flam & Audouze 2001) that raise the ^{7}Li abundance above the cosmologically-interesting value left by Big Bang nucleosynthesis. Nova nucleosynthesis of ^{7}Li is also of interest in that the ^{7}Li is produced as unstable ^{7}Be by the reaction ^{3}He(α,γ)^{7}Be, where ^{3}He is another Big Bang isotope whose subsequent evolution must be accounted for. The β-decay of ^{7}Be with half-life 53.28 d is accompanied in 10.5% of cases by emission of a γ-ray of energy 478 keV that potentially provides a direct measurement of the nova contribution if it can be detected.

Monitoring of the γ-ray sky for novae is important because many events are never detected ($\sim$ 3 out of several dozen per year are discovered, often by amateur astronomers: Harris et al. 1999, 2000, hereafter Papers I and II), raising the possibility that original discoveries of optically-undetected novae may be made by their γ-ray emission alone. This requires experiments with broad fields of view carried on space platforms over periods of the order of years. Data from four such experiments have been analyzed with this purpose in view: the Gamma Ray Spectrometer on the *Solar Maximum Mission* (*SMM*, 1980–1989: see e.g. Leising et al. 1988); BATSE and COMPTEL on the *Compton* Observatory (1991–2000: Hernanz et al. 2000 and Iyudin et al. 1995, 2001); and the Transient Gamma Ray Spectrometer (TGRS) on board *Wind*, from which we will present results from 1995–1997 in this paper. The properties of the TGRS detector, which we describe in §3, are

very suitable for monitoring line emission from novae. The detector has very good energy resolution, which enables Doppler-shifted lines from cosmic sources to be distinguished from background lines at the rest energy; we previously exploited this property in searches for the 511 keV positron annihilation line, which is blueshifted by a few keV in novae (Paper I, Paper II). In this paper we exploit another property of TGRS to search for the 478 keV line, namely the remarkable stability of the instrument's background γ-ray line spectrum (§4).

2. Properties of Classical Novae

Our analysis relies to some extent on the expected properties of the γ-ray line from the nova event. The most important factor in the nucleosynthesis is the composition of the white dwarf upon which the explosion occurs, since material is expected to have entered the burning layer by diffusion upward and to have altered its composition substantially from what was accreted. Most common are expected to be degenerate CO remnants of $\leq 1.25\ M_{\odot}$ left by lower mass red giants. More massive objects up to the limiting stable mass 1.4 $M_{\odot}$ probably have ONe composition. It is not clear where the transition in mass between CO and ONe occurs, or whether indeed there is a range of overlap. Although the general white dwarf mass distribution peaks around 0.6 $M_{\odot}$, the distribution of white dwarf masses in novae is skewed towards higher masses, because the frequency with which nova outbursts recur is a steeply rising function of mass. The ONe remnants and the more massive CO objects $> 1\ M_{\odot}$ are therefore over-represented. A ratio of 2:1 for the two subclasses CO:ONe is often assumed.

Abundance analyses are not available for most novae. Properties may be deduced (with great uncertainty) from the correlations of white dwarf subclass with other observables. It

appears that explosions on CO white dwarfs are less energetic. The ejected masses are of order 10^{-4} $M_{\odot}$ for both subclasses, but CO novae have lower expansion velocities ~ 1000 km s^{-1} (Warner 1995). One of the individual novae that we will consider, the ONe type CP Cru, had a velocity of 2000 km s^{-1} (Della Valle 1996).

Theoretical models predict that CO novae are the strongest sources of the 478 keV γ-ray line (Goméz-Gomar et al. 1998, Hernanz & José 2000) since they may produce about 10^{-10} $M_{\odot}$ of ^{7}Be per event. However, predictions of the ^{7}Be mass fraction produced vary considerably (see e.g. Starrfield et al. 2000a, Hix et al. 2000, and Hernanz & José 2000). Further uncertainty is added by the failure (in general) of models to reproduce the full 10^{-4} $M_{\odot}$ of ejecta, falling short by an order of magnitude or more. The ejecta velocities are also usually underestimated.

Distance estimates for novae are highly uncertain. An empirical relation exists between rate of decline and absolute visual magnitude:

$$M_V = 2.41 \log t_2 - 10.7 \quad \text{for } 5 \text{ d} < t_2 < 50 \text{ d} \tag{1}$$

$$= -9 \quad \text{for } t_2 \leq 5 \text{ d} \tag{2}$$

$$= -6.6 \quad \text{for } t_2 > 50 \text{ d} \tag{3}$$

(Warner 1995), where t_2, the speed class, is the time taken for m_V to increase by 2 from discovery.[4]

Following the explosion in and ejections by thermonuclear runaway, the remaining surface layers undergo hydrostatic H burning on a longer time-scale $\sim$ 1 yr (Shore,

[4] A fuller description of our assumptions and input values to this formula, plus references, is found in Paper I. In two cases (BY Cir and V888 Cen) our result is in very good agreement with that of Shafter (1997) obtained by a variation of the same method. Issues such as visual extinction are common to this method and the Eddington luminosity method described next.

Starrfield, & Sonneborn 1996) and a convective envelope developes. During this time the bolometric luminosity is thought to remain constant at the Eddington value L_{edd} (Warner 1995), but the peak of the emission moves from the optical to the UV as expansion reveals hotter underlying layers. This leads to a second method of estimating distance that has sometimes been used (e.g. Stickland et al. 1981, Evans et al. 1990). Let it be assumed that at visual maximum almost all the flux is at visual wavelengths [as Stickland et al. found for V1668 Cyg (1978)]. The absolute visual magnitude is then known from the Eddington formula $L_{Edd} = 1.3 \times 10^{38} \mu M_{WD}$ erg s^{-1}, where μ is the mean molecular weight and M_{WD} the white dwarf mass in $M_{\odot}$; the distance follows from a comparison of apparent and absolute visual magnitudes.

Post-outburst behavior raises further questions about ^{7}Be observability, which depends on the time-scale on which the expanding envelope becomes transparent to the γ-ray line; it obviously must be well within the 53 d half-life of ^{7}Be if the line is to be seen.[5] We assume that this is the case, following Goméz-Gomar et al. (1998), who predict γ-ray transparency after 5–13 days, depending on the mass and composition of the model. These models also predict large yields of ^{7}Be and 478 keV line fluxes. Our measurements can therefore be regarded as an approach to testing these "optimistic" models.

During 1995–1997 five novae were discovered in the southern hemisphere. They are

[5] Models which directly accelerate a large fraction of the ejecta in the explosion can fulfil this condition (Goméz-Gomar et al. 1998). Another process acting is the ejection of the ^{7}Be in a low-velocity, late-time wind of which part is accelerated by a drag force due to the companion when a common envelope developes between primary and secondary (Livio et al. 1992). It was applied to γ-ray line emission in novae V838 Her (Starrfield et al. 1992, 1993) and V1974 Cyg (Starrfield et al. 1993). Models of this type will not become transparent to γ-rays for ≥ 100 d or two half-lives, severely depleting the detectable ^{7}Be.

listed in Table 1, with composition information where available, and distance estimates from the two empirical methods described above. There are obvious sources of uncertainty in the distance measurements, notably the time of visual maximum (before discovery) and, in the case of the L_{Edd} method, possible neglect of a bolometric correction and super-Eddington velocities in some novae (Schwarz 1999). In addition, there is a single reliable distance measurement (3180 pc for CP Cru from expansion parallax: Downes & Duerbeck 2000). Relative to Paper I (see previous footnote) there are a few changes in Table 1 due to our improved knowledge of the times of visual maxima, thanks to diligent searches of the records of Southern hemisphere amateurs (F. Bateson & A. Jones, private communication).

3. Spacecraft and Instrument

3.1. Introduction to Gamma-Ray Analysis

In space-based γ-ray astronomy the signal from any cosmic source is usually completely dominated by intense ambient background radiation arising from bombardment by the all-pervasive energetic cosmic ray particles, and by the ensuing secondary radiations such as β-decays. The central problem that all experiments must face is therefore how to subtract away this huge background (typically $> 99\%$ of count rate).[6]

In general, the signal has to be modulated. Methods include pointing on and off source rapidly (as with CGRO/*OSSE*, Johnson et al. 1993), modulation in time by a

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[6] It is particularly unfortunate for this analysis that Be is a common choice for space structures (§§3.2, 4.1), being a relatively small source of background at energies *other than* 478 keV).

periodic occulter (e.g. an opaque aperture stop, or the spinning spacecraft body like *HEAO-3*: Mahoney et al. 1982), or even Earth (CGRO/*BATSE*: Ling et al. 2000), or modulation in space by a coded mask illuminating a segmented detector plane (to be used by *INTEGRAL*/SPI: Vedrenne et al. 1999). It is important to note that our work with TGRS used two distinct methods of background subtraction. One is a mechanical occulter (§5), but the other is unique to TGRS — unlike any other experiment TGRS can model its background lines and their temporal behavior accurately enough to perform a usable background subtraction (§4).

The two methods of background subtraction yield results for different "samples" of novae. Occultation measures the averaged collective ^{7}Be emission from the general direction of the GC. Background modeling ought to detect sudden increases in an otherwise predictable background line time history, each the signature of an individual nova. We can search the whole time history, not just the times of the known novae in Table 1, in the hope of detecting nearby undiscovered events.

3.2. Instrument and Detector

The TGRS experiment is located on the south-facing surface of the rotating cylindrical *Wind* body, which points permanently toward the southern ecliptic pole. The spectrometer, a radiatively cooled 35 cm^2 n-type Ge crystal sensitive to energies between 20 keV–8 MeV, is kept at its operating temperature 85 K by a passive radiative cooler constructed mainly of Be and Mg. Apart from 30 mm of Be/Cu alloy that absorbs solar X-rays, it is unshielded, so that in normal (non-burst) operation background spectra are accumulated continuously from the entire southern ecliptic hemisphere. A 1 cm thick Pb occulter attached to the *Wind* body exploits the 3 s rotational period in order to modulate the signal from part of

the sky. The occulter subtends 90° along the ecliptic plane,[7] as seen from the detector, the width of the band thereby occulted being 16° FWHM at around 500 keV.

Owens et al. (1995) reported the results of extensive Monte Carlo simulations of the instrument response as a function of energy and zenith angle. The actual cross section 35 cm^2 is customarily reduced to an "effective" area by factoring in the efficiency of detection at a given energy and angle. Further, the frequent cases where photon energy is only partly lost in the detector cannot be used in the present analysis, since the counts appear in a smooth quasi-continuum at energies below the line energy, and no one count can be unambiguously associated with a weak line like that at 478 keV. Our analysis therefore only uses photons which undergo full energy loss (where in any case the Ge response as a function of energy loss is maximal), i.e. which appear in the channel(s) at the nominal line energy and are referred to as the "photopeak". In these terms, the photopeak effective area of the TGRS detector is $\simeq 15$ cm^2 at 478 keV and zenith angle 0°. It falls sharply with increasing energy but does not vary much with zenith angle (Owens et al. 1995). The instrument response was operationally verified by on-orbit comparisons of γ-ray burst spectra with those obtained by CGRO/*BATSE* (Seifert et al. 1998) and *Wind*/KONUS (Palmer et al. 1996).

The sharp energy resolution of the detector is critical for our analysis. Scintillator detectors like *SMM*/GRS and *BATSE* typically achieve ~ 40 keV resolution around 500 keV. Any line at 478 keV is therefore blended with the positron annihilation line at 511 keV, which is much stronger in both background and background-subtracted spectra. The resolution of TGRS at this energy was nominally about 3 keV FWHM, which was achieved

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[7] The zenith angle of the occulter mid-plane relative to the detector is in fact 84.5° rather than exactly the plane of the ecliptic, which would be 90°. The 5.5° offset was designed to optimize modulation of the GC.

in the early months of the mission (Harris et al. 1998); thereafter resolution degraded due to accumulated damage from cosmic ray impacts. The line profiles also became distorted, with marked tails on the low-energy wings. We limited the data analysis to the period before fall 1997, after which the deterioration became marked (Kurczynski et al. 1999). The detector gain stability also deteriorated on this time-scale. Although the gain shift was not difficult to monitor using the positions of known narrow background lines, the effect on the analysis of occulted data was serious (§5.1).

The TGRS background spectra were binned in 1 keV energy channels over the entire 20 keV – 8 MeV range in 24 minute intervals. The occulted spectra were accumulated in 128 angle bins covering each 3 s revolution of *Wind*. Telemetry constraints did not allow all of these occulted data to be returned in finely-resolved energy bins, however. Data above 1 MeV were discarded. Four energy windows were defined to be 20–150 keV, 150–400 keV, 400–1000 keV, and 479–543 keV, with energy binnings of 2, 4, 8 and 1 keV respectively. The boundaries of the windows changed during the mission as a result of the gain shift.

The unusual orbits followed by *Wind* since launch provide the key to the success of the TGRS background modeling. They have all been highly elliptical (Acuña et al. 1995), and TGRS has thus spent virtually the whole mission in interplanetary space, avoiding major sources of γ-ray background radiation such as Earth albedo γ-rays and energetic trapped charged particles. The chief source of particle bombardment is the Galactic cosmic ray (GCR) flux. There have been very few interruptions in the data stream, generally caused by brief passages of the trapped radiation belts around perigee and by triggering of a special mode of data collection by solar flares and γ-ray bursts. The live time in this data set covers about 90% of the analysis period (Paper II).

The resulting TGRS background lines may be strong, but they are stable enough for our purposes (§4 below). By contrast, experiments in low Earth orbit are plagued

by trapped radiation belt-induced radioactivity, generating background lines varying on a wide variety of β-decay time-scales, many of which never reach equilibrium, and cannot be predicted on either long or short time-scales (Weidenspointner et al. 2001a).

4. Analysis of Background Data

4.1. Qualitative Features

Our analyses of the TGRS background and occulted data sets used quite distinct methodologies that were designed to measure different quantities. Here we focus on the background spectra. A background spectrum is composed of many narrow lines from radioactivity induced by GCR and secondary neutron impacts, superimposed on a continuum. The large mass of Be close to the TGRS detector in the radiative cooler and sunshield (§3) gives rise to a strong line at exactly 478 keV from the interactions ^{9}Be(p,pnn)^{7}Be and ^{9}Be(n,3n)^{7}Be (Naya et al. 1996). We measured the strength of this line in successive spectra from the years 1995–1997. Any sudden increment in the strength would correspond to the signal from a cosmic source of ^{7}Be, and would be confirmed by a subsequent decline on a 53 d half-life. This analysis cannot detect a DC level of 478 keV line emission.

This method clearly relies on the underlying background 478 keV line being very stable, or at least varying in a simple and comprehensible way. As mentioned above, the predominant factor has been radioactivity induced by the GCR flux which varies slowly with the 11 yr solar activity cycle. Solar magnetic modulation is expected to cause the flux to peak around solar activity minimum, which occurred about halfway through our 1995–1997 analysis period. We found evidence for this in the count rate for partial energy

losses $>$ 8 MeV in the detector that is shown in Fig. 1 (top). This is above the energy region characteristic of γ-rays produced by nuclear interactions, so that the background must be due principally to GCR bombardment and the diffuse cosmic background, of which the former only is time-variable. The day-to-day variability of the $>$ 8 MeV rate (top full line) shows a very weak $\sim$ 14 d period that is caused by the *Wind* orbit crossing the neutral current sheet in the interplanetary magnetic field (which varies with the 28 d solar rotation). When integrated over the 53 d time-scale characteristic of nova signals, the count rate shows a modest, smooth variation (histogram) that follows the trends expected for the GCR flux when subject to solar modulation. This pattern of variability was confirmed by a large number of measurements of TGRS background line strengths performed for line identification purposes (Weidenspointner et al. 2001b). Many prompt de-excitation lines were identified that arise from electromagnetic decays of excited nuclear states on submicrosecond time-scales, and it is clear that the intensities of these lines must trace the incident GCR flux effectively instantaneously. These trends are also shown in Fig. 1 (full lines).

4.2. Analysis

The background spectra were summed in 53 d intervals. In each interval the energy range 460–490 keV was fitted with a spectral model consisting of a power law and two lines. There is a strong line at 472.2 keV due to ^{24m}Na from spallation of structural Al, and the 477.6 keV ^{7}Be line from the radiative cooler. The ^{24m}Na line was slightly distorted by the low-energy tailing problem even before the fall of 1997 (§3.2). It was therefore fitted by an asymmetric function

$$A_0 \ \exp\left(-\frac{E-E_0}{\sigma^2}\right) \ + \ A_1 \ \exp\left(\frac{E-E_0}{\nu}\right) \ erfc\left(\frac{E-E_0}{\sigma} \ + \ \frac{\sigma}{2\nu}\right) \tag{4}$$

for amplitudes A_0, A_1, line energy E_0 and width parameters σ and ν (Phillips & Marlow 1976). The line at 478 keV was not fitted by this function, since other factors broaden it (symmetrically) to such an extent that the asymmetry is not significant. One such factor is intrinsic; this line is measured to be somewhat broader than the instrument resolution due to blending with a weak line of ^{55}Co. Alternatively, folding its profile with a Gaussian corresponding to 1000 km s^{-1} (typical for CO novae: §2) has the same effect. A simple Gaussian with this width was therefore included in the fit. A specimen of such a fit is shown in Fig. 2.

The amplitude in terms of count rate was corrected for efficiency using the photopeak effective area as a function of energy and zenith angle (§3.2). The zenith angles of the five known 1995–1997 novae were readily obtained; in the general case (searching for a flux increase when no nova was known to be present) we assumed a zenith angle of 60°, which is the average for the estimated distribution of southern novae (Hatano et al. 1997).

4.3. Results

The time series of the line amplitudes fitted to the 478 keV line in the background spectra is shown in Fig. 3 (*top*). We fitted this time series with a model by which ^{7}Be is created in the instrument by a time-dependent GCR flux, and decays with a half-life 53.28 d. The various curves in Figure 1 suggest that a simple parametrization of the GCR flux would be a linear increase between 1995 January and solar minimum in 1996 June,[8]

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[8] The epoch of solar minimum differs slightly between the various measured quantities (including our own) by which it is defined. Sunspot minimum corresponds to 1996 June. Other possible epochs lie between 1996 May–August.

followed by an abrupt change of slope. Let the corresponding ^{7}Be production rate at time t be $R + Ct$ where R and C are constants and C changes slope at solar minimum. The time-dependent ^{7}Be abundance is then

$$N(t) \ = \ (\frac{R}{\lambda} - \frac{C}{\lambda^2}) \ [1 - \exp{(-\lambda t)}] \ + \ \frac{Ct}{\lambda} \ + \ N(t = 0) \ \exp{(-\lambda t)} \tag{5}$$

where $\lambda = 76.87$ d. We fitted the time series to this function (which has 5 free parameters when account is taken of the discontinuity at solar minimum) and searched for significant sudden flux increases over and above it. This was done by fitting an exponentially decaying function with decay constant λ to each residual data point and the following ones. The fit using Eq. (5) is shown in Fig. 3 (*top*), and the residuals in Fig. 3 (*bottom*).

It is evident from Fig. 3 (*top* and *bottom*) that the function (2) fitted the data very well, so the procedure of fitting the exponential decay could be applied without obvious systematic errors. The clear result in Fig. 3 (*bottom*) is that no flux increase followed by exponential decline was found to appear in the 478 keV line, either at the times of known southern hemisphere novae or at any other time. Clearly no hitherto undiscovered novae were detected by γ-ray line emission using this method. The 3σ upper flux limits for this general case, and for the five known novae, are given in Table 2.

5. Analysis of Occulted Data

5.1. Analysis

Our analysis of the occulted data was designed to measure a quasi-steady, quasi-diffuse 478 keV γ-ray line arising from the integrated emission of many novae that would have occurred towards the GC during the 53 d half-life of ^{7}Be. The principle was suggested by Leising (1988), and was put into practice by Harris, Leising & Share (1991).

Our procedure was essentially identical to that which we previously employed to measure the diffuse positron annihilation spectrum from the GC (Harris et al. 1998). When the count rate in an energy channel is plotted as a function of angle along the ecliptic, those angle bins corresponding to the direction of a source show dips. The amplitude of the dip equals the source count rate at that energy, so that a spectrum of the source is built by taking the source count rate dips in successive energy channels. It is necessary to assume a model of the source's spatial distribution; we chose a Gaussian in ecliptic longitude of FWHM 24°, which Harris et al. (1998) found to be the best estimate for the distribution of the diffuse 511 keV annihilation line (which is compatible with a nova-like distribution of sources: Milne et al. 2001).

The energy channel binning in the region of interest to us around 478 keV was non-uniform and time-variable. This is because, as noted in §3.2, data were only returned at the optimum 1 keV binning in a single 64-keV wide energy window centered approximately on 511 keV, and unfortunately the 478 keV line was on the edge of this window. Energy resolution in the occulted data was therefore bad (8 keV) on the red side, and moreover the transition between well- and coarse-binned data varied during the mission as the high-resolution window shifted with the instrument gain.

Rather than using the complete 1995–1997 Harris et al. (1998) TGRS spectrum, we used a series of spectra summed over 90 d intervals which Harris et al. also generated (for their search for 511 keV line variability). This time-scale happens to be similar to that for significant variability of the gain. We could thus treat the gain shift as a constant and "fix" the location of the high-resolution window boundary in a manner that facilitated spectrum modeling. The 90 d spectra in the range 460–490 keV were fitted by a model consisting of a power law plus a Gaussian line at 478 keV. A typical example of this fit is shown in Fig. 4. Note the abrupt transition from coarse to fine binning in the middle of the energy range.

5.2. Results

The measured 478 keV line fluxes during 90 d intervals are shown in Fig. 5. These results may be combined to give the total measured quasi-steady flux from the GC. It is clear that no line is detected, within limits which are given in Table 2. The sensitivity of this search is degraded by a factor 4–5 relative to that of the background-modeling method. This is mainly due to the gain shift problem mentioned above. Table 2 also shows earlier measurements by *SMM* for both individual novae and the quasi-steady integrated GC flux (Harris et al. 1991). Note that the integrated flux measurements are not exactly comparable, since the *SMM* value comes from a very broad region $\sim 130^\circ$ across around the GC, whereas the TGRS value reflects the signal from the $16^\circ \times 90^\circ$ occulted region only.

6. DISCUSSION

6.1. Comparison of TGRS Results with Theory

From the flux upper limits in Table 1 we calculate the ^{7}Be abundances in the sources, given the distances. Our limits improve upon the *SMM* values by an order of magnitude for individual events, and by a factor 2 for the integrated flux from the GC. Unfortunately we do not obtain proportionate improvements in the limits on the ^{7}Be abundances from these fluxes, for two reasons. In the case of individual novae, by misfortune the TGRS sample lay at greater distances than the *SMM* sample. In the case of the GC, the measurement methods (*SMM* or TGRS occulter) return ^{7}Be abundances integrated over the unknown number of novae that are simultaneously present, and thus depend on the uncertain Galactic nova rate R_N and on the aperture of the instrument. Since the effective aperture of TGRS

is smaller than the $\sim 130°$ aperture of *SMM*, the upper limit implied by a given γ-ray flux is divided among fewer novae.

Comparisons with theory must take into account the shortcomings and uncertainties in nova models (see §2). For our purposes, the prediction of any nova's ^{7}Be mass may be factored into the product of the ejected mass M_{ej}, and the mass fraction X_7 of ^{7}Be in it. In the favorable case of a massive CO nova, "optimistic" models such as Gómez-Gomar et al. (1998) suggest values $M_{ej}/M_\odot \sim X_7 \sim 10^{-5}$. Both of these values may be underestimates, leading to yet more optimistic scenarios that were proposed earlier by Clayton (1981).

There are two arguments for this kind of scenario.[9] First, as pointed out in §2, there is a "missing mass" problem (Starrfield et al. 2000b): nova models in general predict M_{ej} that are much too low. Measured ejecta masses range from $\sim 10^{-5}$–10^{-3} $M_\odot$ (Warner 1995); the mean value is probably $\sim 2 \times 10^{-4}$ $M_\odot$ (Gehrz et al. 1998). As for X_7, it was pointed out by Starrfield et al. (1978) that, whereas models assume that the abundance of ^{3}He in the gas accreted onto the white dwarf is usually solar, this is probably not the case. The ^{3}He abundance should be enhanced in the donor star due to synthesis of this isotope in the pp chain, and convection will mix the ^{3}He-rich material into the surface layers which are transported to the white dwarf. Older main sequence star models suggested ^{3}He enhancements ~ 10 times solar, while more recent models suggest a value about 50% of this (Morel et al. 1999). However, Boffin et al. (1993) showed that, contrary to what was assumed by Starrfield et al. (1978), the yield of ^{7}Be from ^{3}He$(\alpha,\gamma)^7$Be in novae is not proportional to the ^{3}He abundance, but to its logarithm. The model yields of ^{7}Be are then probably enhanced by less than a factor 2.5 by the ^{3}He enhancement. Most of the possible

[9] We assume that the factors M_{ej} and X_7 can be varied independently. This is unlikely to be the case in actual models, although Starrfield et al. (1997) made a similar assumption in order to generate γ-ray predictions.

variation in the product is thus due to uncertainty in M_{ej}, of which our upper limits may be a test.

For the purpose of comparison with our upper limits, we show in Table 2 the fluxes that would be expected from each nova (and from the GC) if optimistic values $M_{ej} = 2 \times 10^{-4} M_{\odot}$ and $X_7 = 2.5 \times 10^{-5}$, similar to the old values of Clayton (1981), are assumed. In all cases, our limits lie above the expected fluxes; however some of the individual cases are of interest. Our limit for BY Cir is only a factor ~ 6 above the expected value, even better than the *SMM* limit for the much closer event V482 Cen. These happen to be the only verified CO novae in the two samples. Thus we can exclude highly optimistic estimates of the ejecta masses, exceeding 1–2$\times 10^{-3}$ $M_{\odot}$, for two members of this class of nova. Given that CP Cru is the only ONe event in the TGRS sample, with a limit on the flux 40 times the expected value, the same reasoning produces an upper limit $M_{ej} < 8 \times 10^{-3}$ $M_{\odot}$ for this class of event, improving on the *SMM* limit by almost a factor 10. From our result for the general case, we also exclude any undiscovered nova with optimistic "Clayton-like" parameters having occurred within 1.1 kpc during 1995–1997; or any undiscovered nova of the highest-yielding Gómez-Gomar et al. (1998) type (CO, 1.15 $M_{\odot}$) within 134 pc.

6.2. Possible Application to *INTEGRAL*

This work has established the feasibility of the time series modeling method of background subtraction (§4), at least for resolvable lines (not too severely blended), for γ-ray emitters having appropriate time-scales — and especially for stable background lines amenable to very simple temporal models. An obvious improvement would be to model blended line complexes of astronomical interest, which would require much more sophisticated modeling than our semi-empirical approach. Thus, work is under way to

model the TGRS background spectrum ab initio, from the mass model and the GCR flux (Weidenspointner 2001c).

Some of the features that make this approach possible are included in the upcoming *INTEGRAL* mission, in particular a high-resolution Ge spectrometer (SPI), and a highly elliptical orbit which, like that of TGRS, avoids Earth's trapped radiation belts (Winkler 1996). If the background lines prove to be stable enough, it may be possible to apply our method to the off-source SPI background.

Relative to TGRS, SPI has much greater sensitivity, close to 10^{-5} photon cm^{-2} s^{-1} at 478 keV. The best-case theoretical models in Table 2 (CO, 1.15 $M_{\odot}$) are then detectable at a distance of 500 pc (Hernanz & José 2000). The more optimistic parameters $M_{ej} = 2 \times 10^{-4}\ M_{\odot}$, $X_7 = 2.5 \times 10^{-5}$, similar to those of Clayton (1981), that we discussed in §6.1 and assumed in column 5 of Table 2 for the purpose of flux comparisons, would enable SPI to make detections out to 3.4 kpc. A detection distance of this order intercepts $\sim 0.8\%$ of the global nova distribution (Paper II), two-thirds of which are of CO subtype. If *INTEGRAL* continues beyond its 2-year nominal mission to the 5-year extended mission, the number of novae it can be expected to detect is $\sim 0.03 R_N$, which is ~ 1.3 for realistic values of $R_N \sim 50$ yr^{-1}. The prospects for a SPI observation improving on our results are therefore quite good.

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Fig. 1.— Variation of monitors of GCR intensity through 1996 solar minimum. (Top, full line) Count rate at energies > 8 MeV on 1 d time-scale. (Top, histogram) Count rate at energies > 8 MeV on 53 d time-scale. (Lower full lines) Intensities of prompt instrumental de-excitation lines as measured by local fits with power law and Gaussian profile. Line ID — 140 keV, ^{75}Ge(139.7–g.s.) — 198 keV, ^{71}Ge cascade (198–g.s) sum peak — 440 keV, ^{23}Na(439.9–g.s.).

Fig. 2.— TGRS background spectrum during 1995 July 31–1995 September 22, fitted by power law and lines at 472 keV (^{24m}Na) and 478 keV (^{7}Li).

Fig. 3.— (*Top*) Time series of 478 keV line strengths in 53 d spectra, fitted to a model of the behavior of the instrumental background line (full line). Arrows — estimated eruption times of known southern novae: in sequence, BY Cir, V888 Cen, V4361 Sgr, CP Cru, and N Sco 1997. (*Bottom*) Residual flux after subtracting the above model. The value of χ^2 per degree of freedom for the fit is 0.4.

Fig. 4.— GC spectrum around 478 keV from TGRS occultation analysis, for the period 1995 December 25–1996 March 22, fitted by a hypothetical cosmic line at 478 keV superimposed on a power law. Line amplitude is $-4.7 \pm 7.5 \times 10^{-5}$ γ cm^{-2} s^{-1}.

Fig. 5.— Time series of GC fits to 90 d spectra as in Fig. 4. The χ^2 per degree of freedom for the fit is 1.0.

Nova	White Dwarf	Possible date of maximum	m_V at discovery	t_2, days	Distance, Eq. (1–3), pc[a]	Distance, L_{Edd}, pc[b]
BY Cir	CO	1995 Jan 21.0 – Jan 27.3	7.2	~ 20	3240–4000	2370–3030
V888 Cen		1995 Feb 22.0 – Feb 23.3	7.2	~ 6	6060–6970	2450–3720
V4361 Sgr		1996 Jun 19.6 – Jul 11.5	10.0	53	4640–6785	5070–10280
CP Cru	ONe	1996 Aug 22.0 – Aug 27.0	9.25	5.2	6770–16300	3100–7500
V1141 Sco		1997 Jun 2.1 – Jun 5.1	8.5	4.5	6830–8340	2460–6860

[a] Uncertainty does not include observational scatter around the empirical law Eq.(1–3).

[b] Uncertainty does not include bolometric correction at visual maximum.

Table 1: Novae observable by TGRS, 1995–1997

Target	Distance pc[a]	Zenith Angle	Flux [b] γ cm^{-2} s^{-1}	Expected [c] γ cm^{-2} s^{-1}	Implied ^{7}Be mass $M_\odot$ per nova[b]
Individual Novae					
Undiscovered nova		60°	1.0×10^{-4}		
BY Cir	3160	45°	6.8×10^{-5}	1.1×10^{-5}	3.0×10^{-8}
V888 Cen	4800	42°	6.3×10^{-5}	4.9×10^{-6}	6.4×10^{-8}
V4361 Sgr	6700	95°	1.1×10^{-4}	2.5×10^{-6}	2.2×10^{-7}
CP Cru	3180 [d]	37°	8.8×10^{-5}	2.2×10^{-6}	3.9×10^{-8}
Nova Sco	6120	97°	1.6×10^{-4}	3.0×10^{-6}	2.7×10^{-7}
V1370 Aql [e]	3500		1.2×10^{-3}	1.8×10^{-6}	6.3×10^{-7}
QU Vul [e]	3000		7.5×10^{-4}	2.5×10^{-6}	3.1×10^{-7}
V842 Cen [e]	1100		9.6×10^{-4}	9.3×10^{-5}	5.2×10^{-8}
GC Integrated					
TGRS	8000	84.5°	7.7×10^{-5}	$7.8R_N \times 10^{-8}$	$3.4 \times 10^{-6}/R_N$ [f]
SMM	8000		1.5×10^{-4}	$1.6R_N \times 10^{-7}$	$3.5 \times 10^{-6}/R_N$ [f]
Theory [g]					
CO 0.8 $M_\odot$	1000		1.8×10^{-6}		8.0×10^{-11}
CO 1.15 $M_\odot$	1000		2.5×10^{-6}		1.1×10^{-10}
ONe 1.15 $M_\odot$	1000		3.6×10^{-7}		1.6×10^{-11}
ONe 1.25 $M_\odot$	1000		2.7×10^{-7}		1.2×10^{-11}

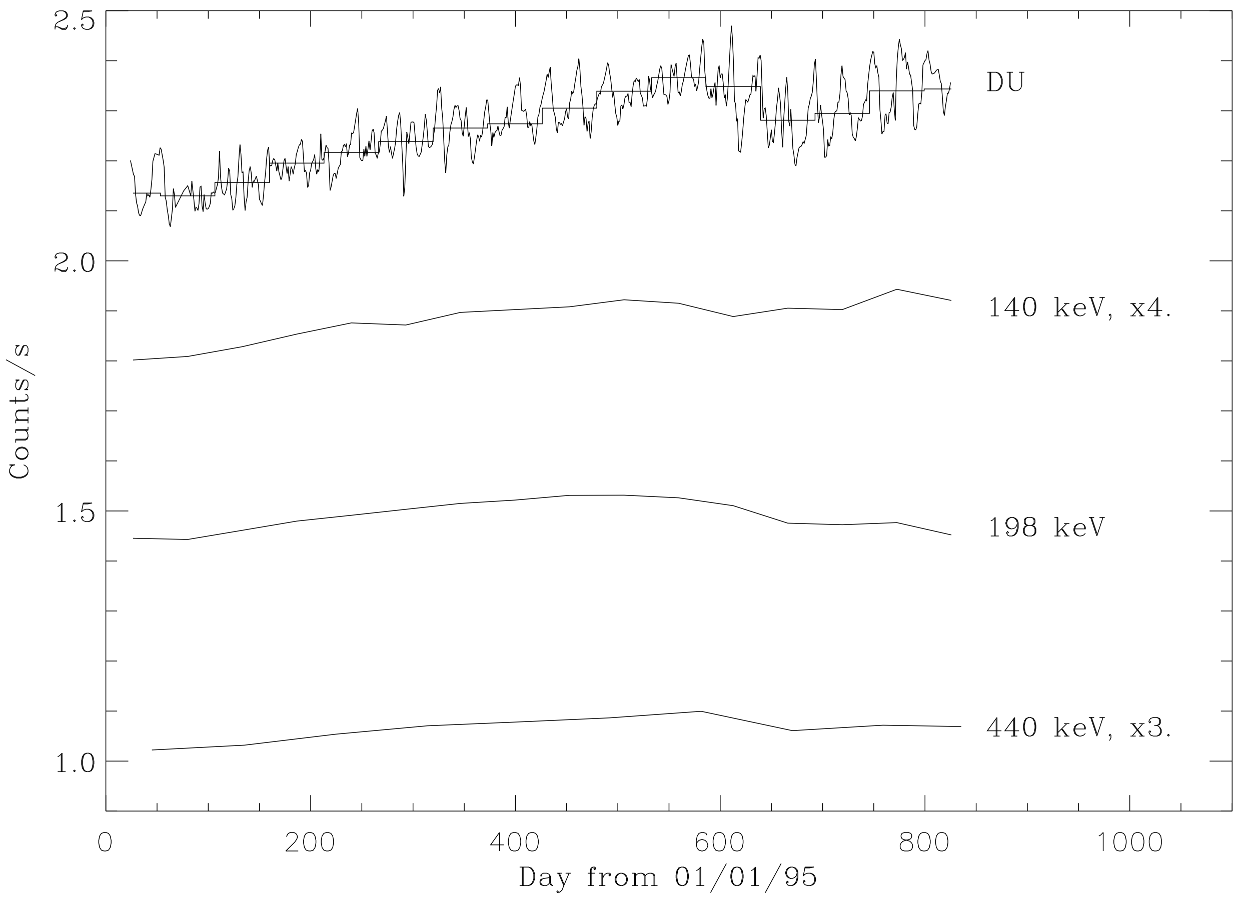
[a] Simple mean of estimates in columns 6 and 7 of Table 1, unless otherwise noted.

[b] 3 σ upper limit.

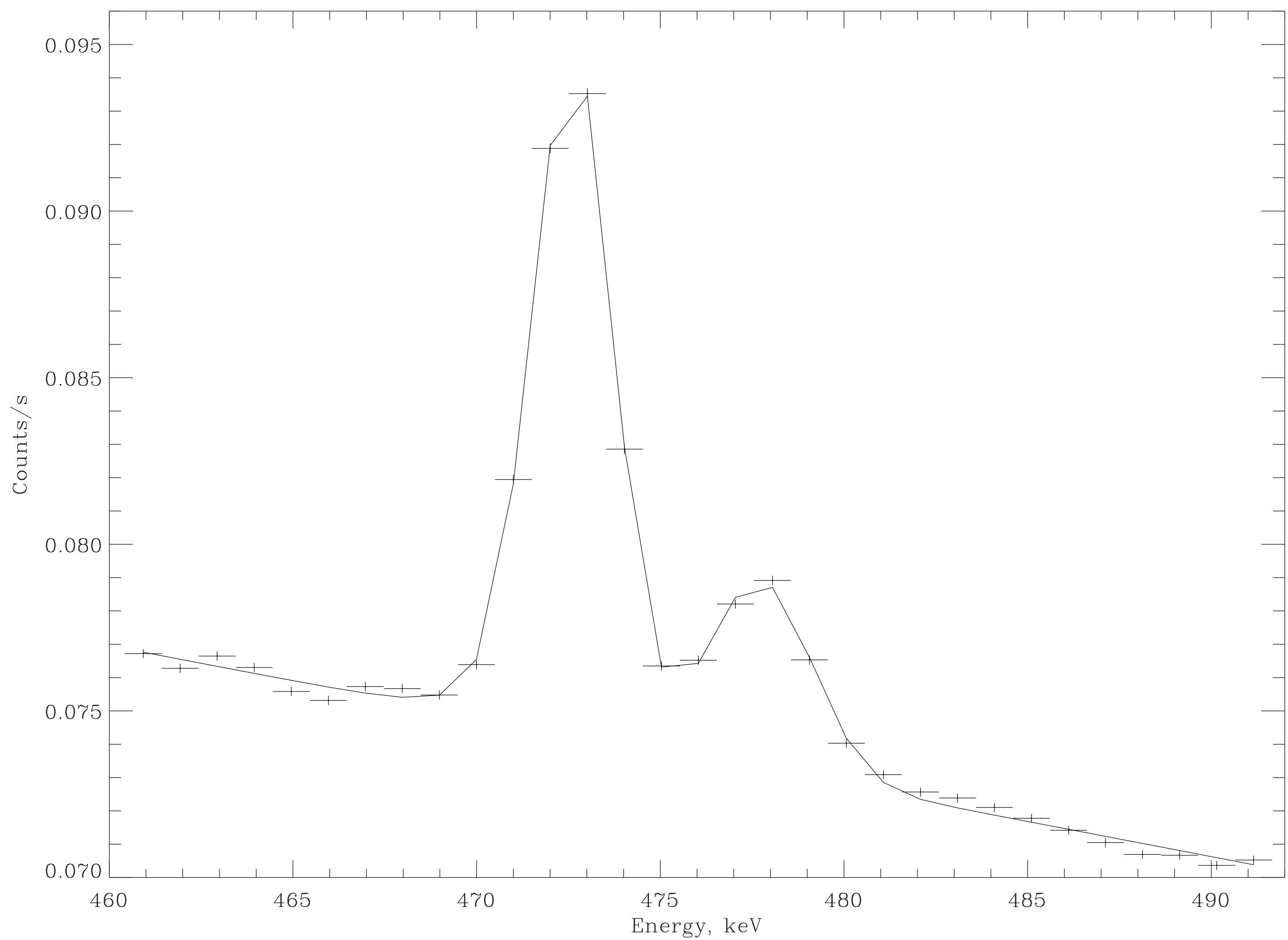
[c] Assumes "optimistic" parameters (see §6) of 2×10^{-4} $M_\odot$ of ejecta (as observed: Warner 1995) enriched to mass fractions 2.5×10^{-5} for CO subclass and 5×10^{-6} for ONe subclass.

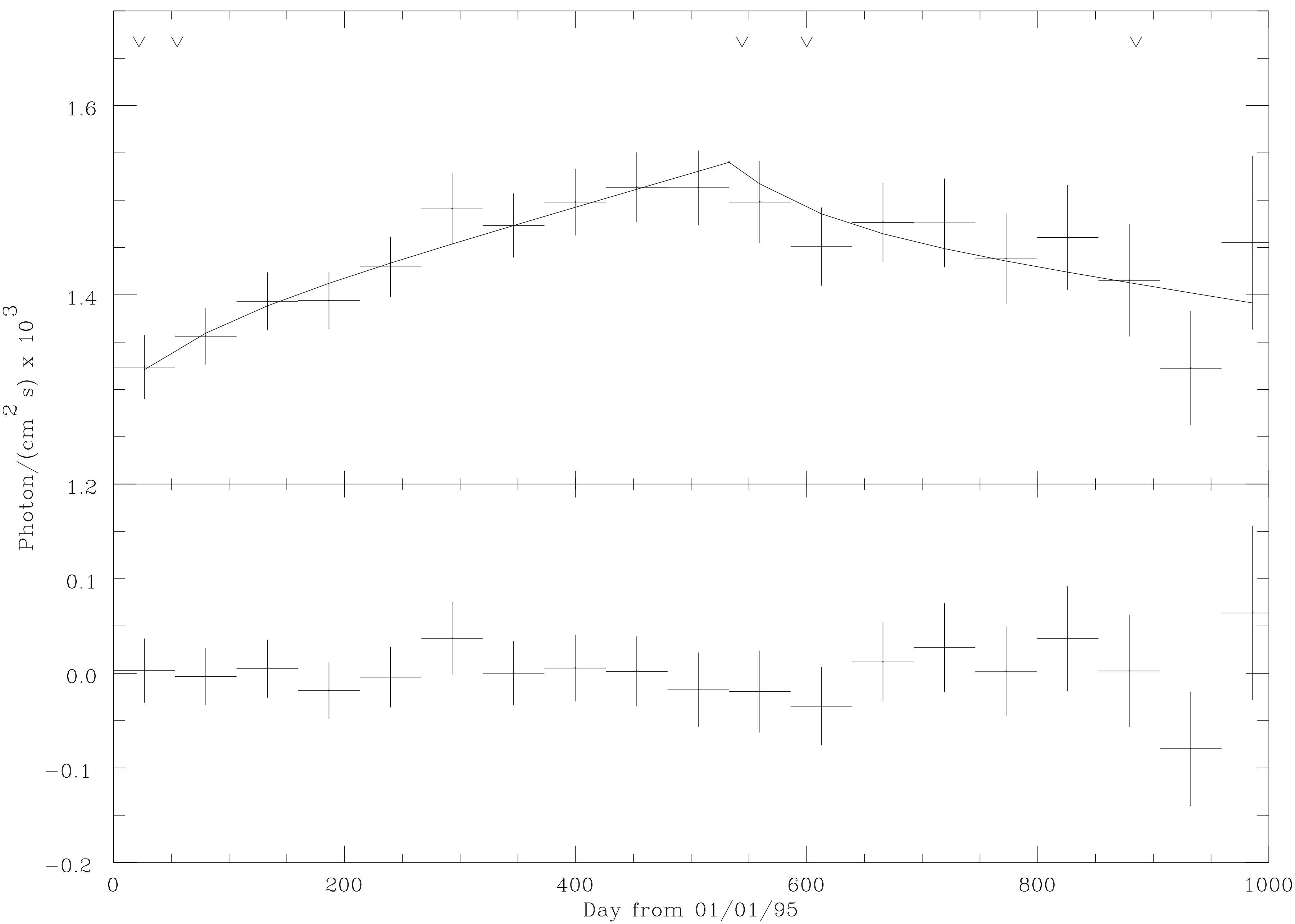
[d] From expansion parallax measurement (Downes & Duerbeck 2000).

[e] Measured by *SMM* (Harris et al. 1991). Subclasses: ONe (V1370 Aql 1982 and QU Vul

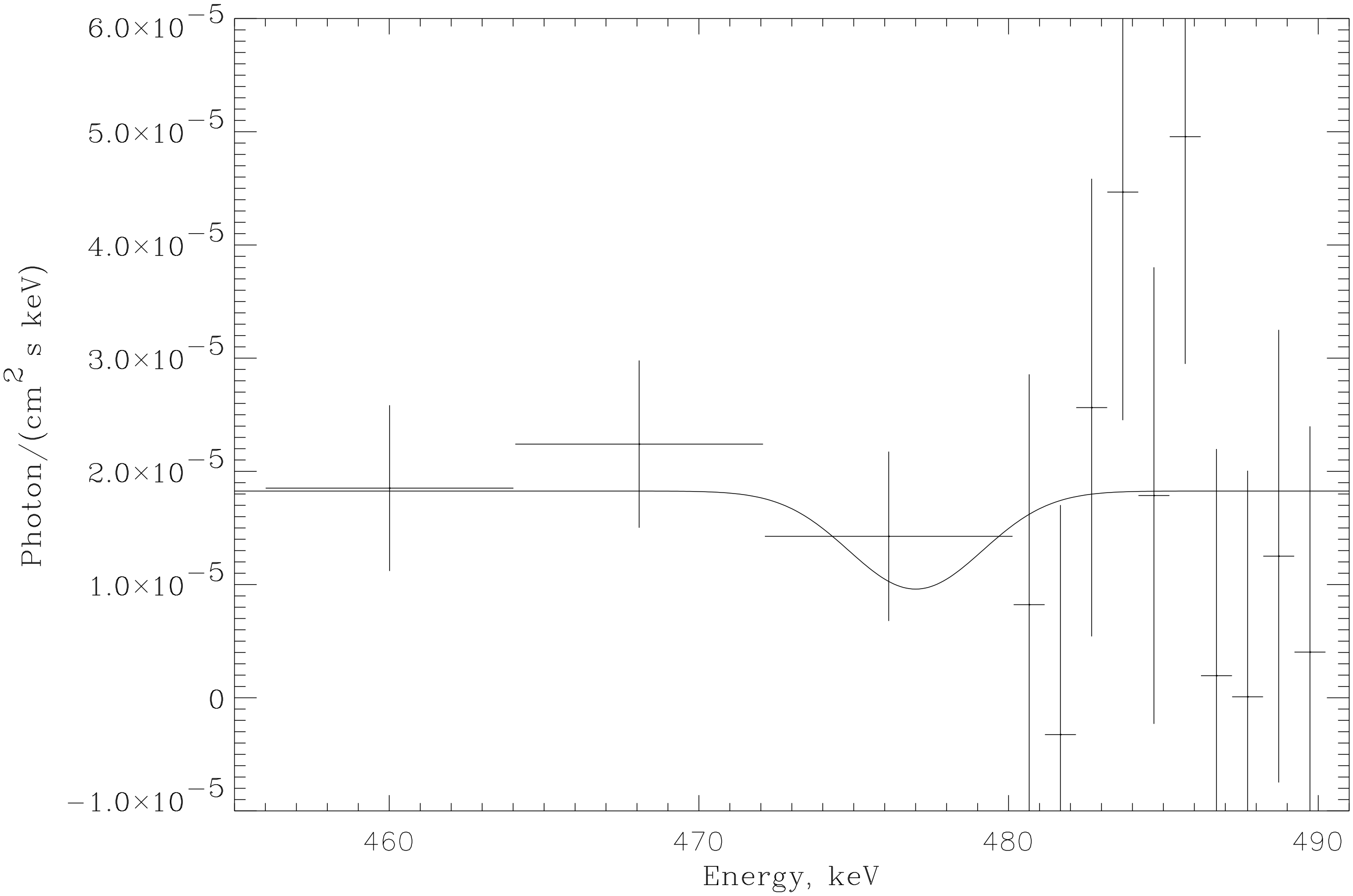


2.5
2.0
1.5
1.0
Counts/s
DU
140 keV, x4.
198 keV
440 keV, x3.
0
200
400
600
800
1000
Day from 01/01/95

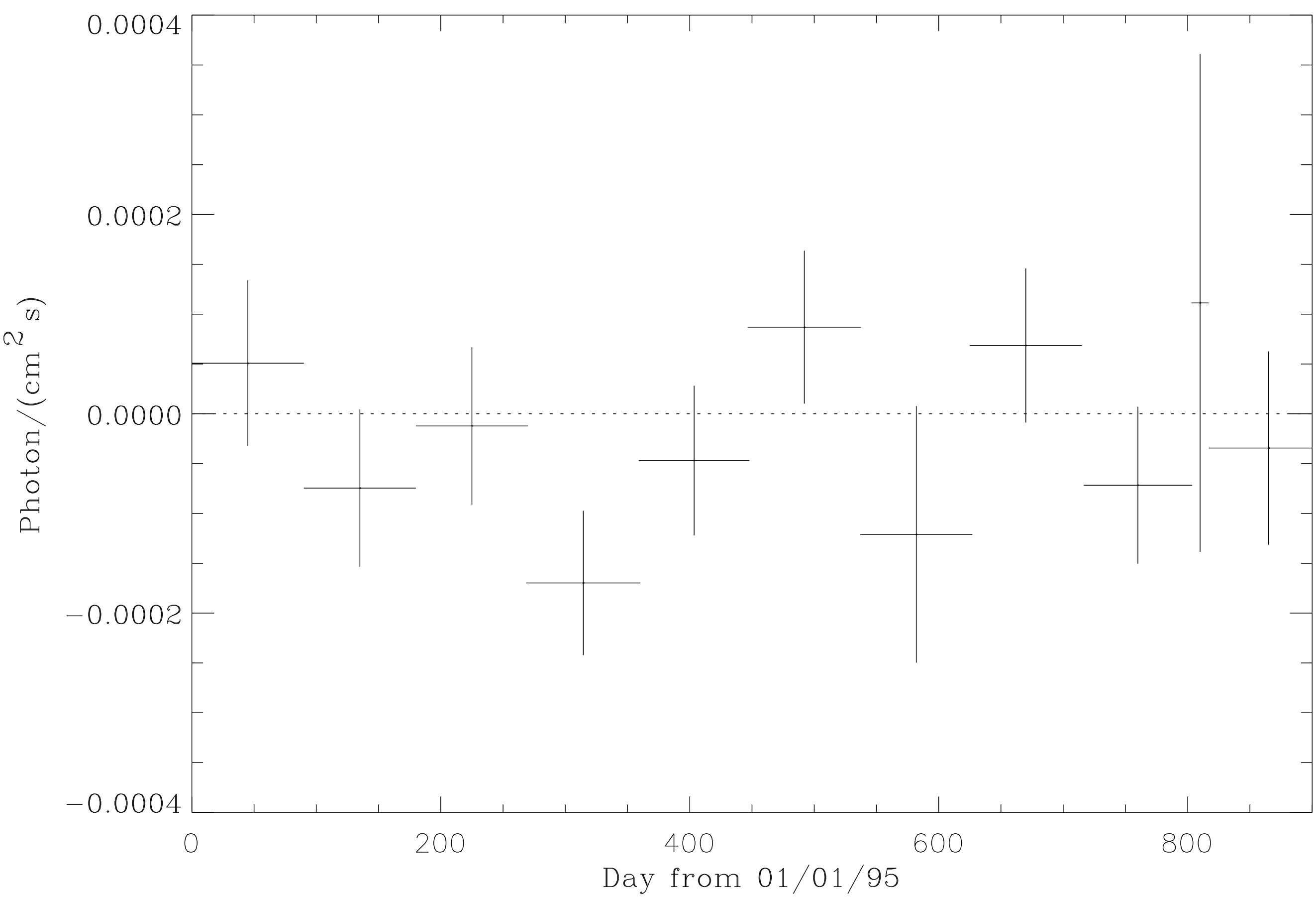

0.095
0.090
0.085
0.080
0.075
0.070
Counts/s
460
465
470
475
480
485
490
Energy, keV



Photon/(cm^2 s) x 10^3
1.6
1.4
1.2
0.1
0.0
−0.1
−0.2
0
200
400
600
800
1000
Day from 01/01/95



6.0×10⁻⁵
5.0×10⁻⁵
4.0×10⁻⁵
3.0×10⁻⁵
2.0×10⁻⁵
1.0×10⁻⁵
0
−1.0×10⁻⁵
Photon/(cm² s keV)
460
470
480
490
Energy, keV



0.0004
0.0002
0.0000
−0.0002
−0.0004
Photon/(cm^2 s)
0
200
400
600
800
Day from 01/01/95